

Recent Heavy Flavor and Quarkonia Measurements by the PHENIX Experiment

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Abstract.

The discovery at RHIC of large high- p_T suppression and flow of electrons from heavy quarks has altered our view of the hot and dense matter formed in central Au+Au collisions at $\sqrt{S_{NN}}=200$ GeV. Meanwhile, the nuclear modification of the J/ψ yield has shown no clear energy density dependence when comparing measurements at CERN-SPS and at RHIC energies and measurements in different rapidities. PHENIX has carried out a comprehensive study of heavy quarks including a baseline measurement of heavy flavor, J/ψ and Υ in $p+p$ collisions, and the fractional contribution to J/ψ from ψ' and χ_c decays. Initial state and other cold nuclear matter effects were studied using a large data set collected in d +Au collisions. No strong heavy flavor suppression was observed at mid-rapidity using this data and in Cu+Cu collisions. We found a significant suppression of J/ψ in d +Au for all rapidity ranges covered by PHENIX. This suppression is stronger at forward rapidity and has no linear dependence with the nuclear thickness. A similar suppression trend was also observed for $\Upsilon(1S+2S+3S)$ but with large statistical uncertainties. A more precise measurement of the J/ψ yield in Au+Au collisions in the forward rapidity is consistent with our previous observation. No significant collision energy dependence was observed in the centrality dependence of the J/ψ suppression when looking at the data collected in Au+Au collisions at $\sqrt{S_{NN}}=62$ GeV and $\sqrt{S_{NN}}=39$ GeV, supporting previous comparisons with CERN-SPS data.

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1. Introduction

One of the most striking discoveries during the RHIC operation is the large suppression at high p_T and flow of electrons from open heavy flavor in Au+Au collisions [1] (Figure 1-left). Final state energy loss based on gluon radiation, which describes the suppression of light mesons, is supposed to get smaller with the increasing of the quark mass [2, 3, 4]. Recent heavy flavor measurements in d +Au and Cu+Cu collisions performed in the PHENIX detector explored the possibility that initial state effects is responsible for the large suppression observed in Au+Au collisions. Section 2 presents the results from

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these measurements along with some discussion concerning the baseline measurement in $p+p$ collisions and future measurements using vertex detectors.

Another puzzling observation is the similar J/ψ suppression at RHIC and CERN-SPS energies as well as the stronger suppression at forward rapidities [5, 6]. The energy density of the medium formed at RHIC is larger than that found in the CERN-SPS experiments [7] giving more room for the color screening of charmonium at RHIC [8]. On the other hand, the energy density should be rapidity independent, in contradiction with the observation of a rapidity dependence of the J/ψ suppression. A system/energy consistent study of the J/ψ production has been carried out including i) the feed-down fraction from excited charmonium states, ii) hints about the production mechanism in $p+p$ collisions, iii) a systematic study of the geometry dependence of the nuclear modification in $d+Au$ collisions and iv) reduction of the statistical and systematic uncertainties of the forward rapidity measurement in Au+Au collisions. The collision energy dependence of the J/ψ suppression was also studied with Au+Au collisions at $\sqrt{S_{NN}}=62$ GeV and $\sqrt{S_{NN}}=39$ GeV. These studies are summarized in Section 3 which also reports the first measurements of Υ production in $p+p$ and $d+Au$ collisions.

2. Heavy Flavor

The differential cross section of electrons from heavy flavor measured in $p+p$ collisions at mid-rapidity [9] is in agreement with the STAR data measured at the same energy [10]. This result is ~ 1.5 larger than Fixed-Order-Leading-Log (FONLL) pQCD calculation [11], but still in agreement within the experimental and theoretical uncertainties. If a $\sqrt{\langle k_T^2 \rangle}$ smearing of 1 GeV/ c is introduced in a FONLL based heavy flavor event generator, the calculated heavy flavor yield matches the central value of the experimental result [12]. One caveat is that $\sqrt{\langle k_T^2 \rangle}$ was found to be $2.68 \pm 0.07(\text{stat}) \pm 0.34(\text{sys})$ GeV/ c when analysing dihadron correlation [13]. Preliminary result towards an extended p_T coverage can be found in [14]. The same measurement at forward rapidity is between 2 and 4 times larger than the central FONLL calculation with no k_T smearing, being in a marginal agreement at $p_T > 3.5$ GeV/ c [15].

We investigate the importance of expected initial state effects in the heavy flavor suppression observed in Au+Au (Figure 1-left). These effects include gluon distribution modifications (Figure 3-left) caused by shadowing, gluon saturation, initial state parton energy loss and multiple scattering. The preliminary result of the nuclear modification factor (R_{AA}) of single electrons from heavy flavor measured in $d+Au$, where no hot-dense medium is formed, suggests a small contribution of the initial state effects in the heavy flavor suppression at mid-rapidity [14]. A similar R_{AA} pattern was also observed in central Cu+Cu and peripheral Au+Au collisions (Figure 1-right) suggesting a dominance of cold nuclear matter in Cu+Cu collisions and the 60% most peripheral Au+Au collisions.

The PHENIX detector is entering a new era with the installation of silicon vertex detectors which can measure the secondary vertex of decayed particles. This

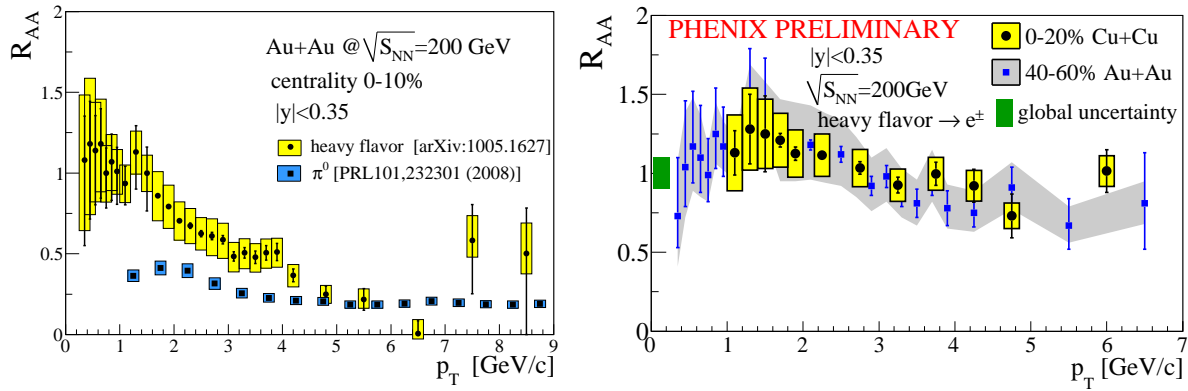


Figure 1. (Color online) (Left) Nuclear modification factor (R_{AA}) of electrons from heavy flavor decays and π^0 in central Au+Au events. (Right) R_{AA} of electrons from heavy flavor decays in central Cu+Cu and peripheral Au+Au collisions.

measurement will allow the rejection of leptons from light quark mesons and charm/bottom separation. The vertex detector (VTX) [16] placed at $|\eta| < 1.2$ and almost full azimuthal coverage is already operational. The forward vertex detector (FVTX) [17] will be installed for the 2012 Run covering $1.2 < |y| < 2.4$ and all azimuthal angles. Measurement of charm and bottom yields as well as their coupling with the medium using correlation with hadrons in a broad rapidity coverage will provide tight constraints for the current energy loss models in hot and dense matter as well as a more direct study of the initial state effects in the heavy flavor production.

3. Quarkonium

A new measurement of the J/ψ R_{AA} in the rapidity range $1.2 < |y| < 2.2$ (Figure 2) [18] has been released. The new data was collected during the 2007 Run with an integrated luminosity three times larger than in the 2004 Run used in the previous results [5]. The level-2 trigger based on a minimum dimuon invariant mass was not required in this new data. This allowed a reduction of the uncertainties in determining the combinatorial and correlated backgrounds, hence the systematic uncertainties were also reduced. This new result is consistent with the previous result confirming the observation of a stronger suppression of J/ψ at forward rapidity.

Extrapolations of the cold nuclear matter were evaluated in Figure 2 using 31 variations of the gluon distribution modification EPS09 [19] plus several assumptions for the J/ψ breakup cross section in hadronic matter. The impact parameter dependence in EPS09 was introduced as a linear dependence with the density weighted nuclear thickness. No combination of EPS09 and breakup cross section can describe the stronger suppression at forward rapidity. The addition of initial state parton energy loss does not change the picture. The J/ψ measured in the rapidity $1.2 < y < 2.2$ is mostly formed from a small- x gluon (which is suppressed according to EPS09) and a large- x gluon (which is enhanced), hence the final J/ψ suppression is close to that obtained at

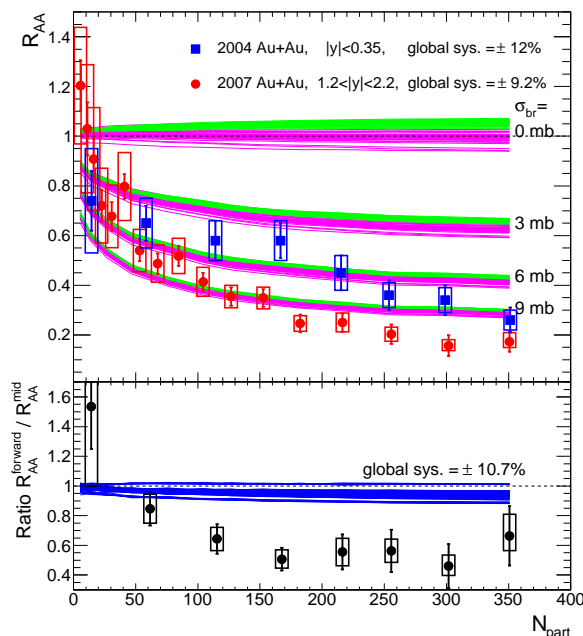


Figure 2. (Color online) (Top) Nuclear modification factor (R_{AA}) of the J/ψ yield in Au+Au collisions at $\sqrt{s} = 200$ GeV in mid and forward rapidities. (Bottom) Ratio between forward/mid rapidity modifications in the bottom panel [18]. Green(magenta) or light gray(dark gray) curves corresponds to R_{AA} calculations for the mid(forward) rapidities using parton distribution modification EPS09 [19] with linear dependence with nuclear thickness + different breakup cross sections σ_{br} followed by their corresponding ratio in the bottom panel.

mid-rapidity according to the this EPS09 based calculation.

The details of the cold nuclear matter effects in the J/ψ production were studied with our large data sample collected during the 2008 d +Au run [20], with special emphasis to its geometrical aspects. The nuclear modification factor was measured relative to the yield in p + p collisions (R_{dA}) and peripheral events (R_{cp}). The J/ψ is suppressed in all rapidity range covered by PHENIX with a stronger suppression towards the forward region. Figure 3-right shows R_{cp} vs. R_{dA} for 12 rapidity bins. The way the nuclear modification depends on the nuclear thickness§ determines the position of the (R_{cp}, R_{dA}) points. The figure shows curves representing exponential, linear and quadratic dependencies. The conclusion is that the linear dependence commonly used to introduce the impact parameter in calculations using parton distribution modifications is not supported. Studies using different functions of nuclear thickness for the nuclear modification have now been carried out.

The production mechanism of charmonium and feed-down fraction of ψ' and χ_c decays to J/ψ are also important inputs to describe the suppression in Au+Au collisions. Charmonium could traverse part of the nuclear matter as a pre-resonant state before neutralization if it is formed as a color octet. The rapidity and p_T dependence

§ Nuclear thickness considering a Wood-Saxon density in the Glauber calculation.

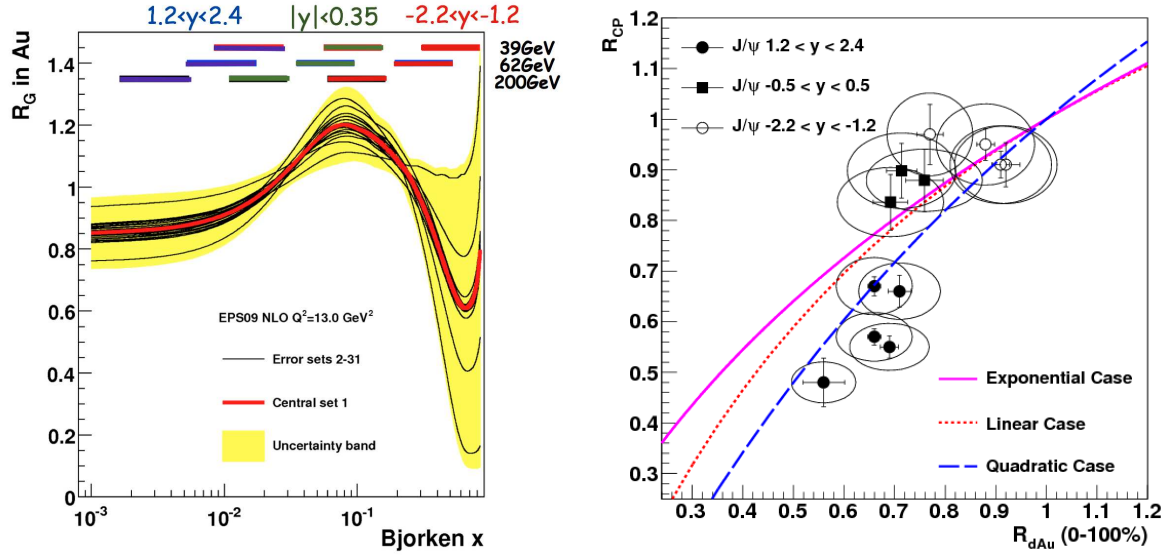


Figure 3. (Color online) (Left) Bjorken- x dependence of the gluon distribution modification (EPS09) [19] and corresponding PHENIX coverage for $\sqrt{s_{NN}} = 200 \text{ GeV}$, $\sqrt{s_{NN}} = 62 \text{ GeV}$ and $\sqrt{s_{NN}} = 39 \text{ GeV}$ collisions. (Right) J/ψ nuclear modification relative to peripheral events (R_{cp}) vs. modification relative to $p+p$ collisions (R_{dA}) along with exponential, linear and quadratic nuclear thickness dependencies [20].

of the differential cross section [21] and polarization at mid-rapidity [22] of inclusive J/ψ were measured in $p+p$ collisions. According to recent NLO calculations [23, 24], the inclusive yield can be described only if color octet intermediate states are dominant. The J/ψ polarization observed at mid-rapidity is small and consistent with recent color singlet and color octet dominant estimations. The polarization measurement is also important to reduce uncertainties in the detector acceptance of J/ψ decays.

ψ' and χ_c yields were measured for the first time at RHIC revealing that $(9.6 \pm 2.4)\%$ of the J/ψ yield comes from ψ' decays whereas $(32 \pm 9)\%$ comes from χ_c decays at mid-rapidity [21]. These charmonium states are supposed to dissociate around the critical temperature T_c according to all spectral function studies up to date ([25] for a nice review). Hydro calculations fitted to thermal photons measured by PHENIX suggest initial temperatures at RHIC between $1.7\text{--}3.5 T_c$ [26]. If ψ' and χ_c are totally dissociated, $(42 \pm 9)\%$ of the J/ψ yield is suppressed in Au+Au collisions which still is not enough to describe the total J/ψ suppression observed at mid-rapidity in Au+Au central collisions. The measurement of ψ' nuclear modification factor in Au+Au collisions is one of the goals for the PHENIX quarkonia program which can be achieved with the expected increasing luminosity and the improvement in the mass resolution in the forward arms after the installation of the FVTX.

The other puzzle involving the J/ψ production in A+A collisions is the apparent same suppression observed at RHIC and lower energy CERN-SPS experiments. The measurements were obtained using different apparatus and different rapidity ranges. A consistent study of the collision energy dependence of the J/ψ nuclear modification

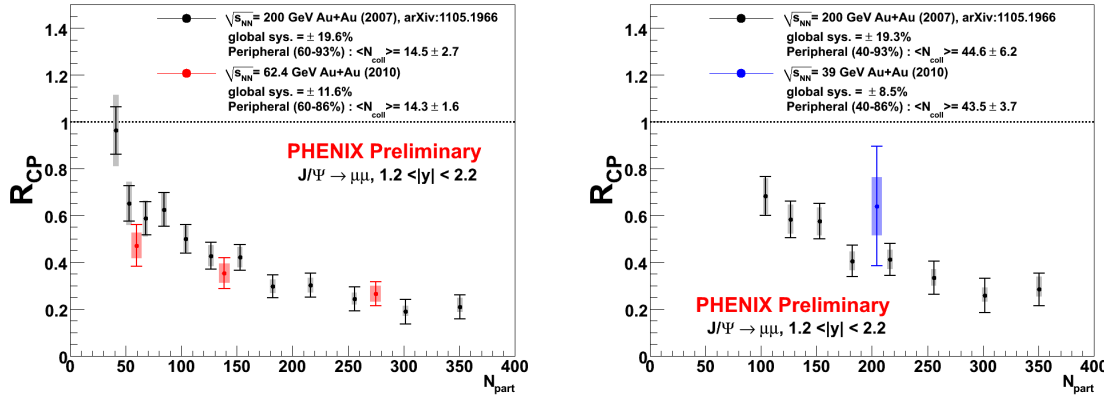


Figure 4. (Color online) Nuclear modification factor of J/ψ relative to peripheral collisions vs. number of nucleons participants in Au+Au collisions at $\sqrt{s_{NN}} = 62$ GeV and $\sqrt{s_{NN}} = 39$ GeV compared to the corresponding $\sqrt{s_{NN}} = 200$ GeV using the same peripheral centrality as a reference.

was carried out during the 62 GeV and 39 GeV Au+Au runs in the forward rapidity. There is no $p+p$ reference for these energies up to date. Figure 4 shows the dependence with the number of nucleons participants of R_{cp} for these energies and 200 GeV. The comparison with 39 GeV is not conclusive because of the large statistical uncertainty. Giving the current uncertainties, the J/ψ suppression in 62 GeV is consistent to what was observed in 200 GeV. There is a small trend for a stronger suppression in 62 GeV when the number of participants is less than 100. The Bjorken- x region covered by the central and forward detectors in PHENIX scales with $s^{-1/2}$ as shown in Figure 3-left. Hence, the observed initial state effects in the final suppression should behave differently when changing the collision energy. Estimations for R_{cp} from cold nuclear matter and measurements in $d+Au$ collisions at these low energies can shed some light on the importance of these effects in Au+Au collisions. Another caveat in this observation is that the energy density of 62 GeV and 200 GeV is different for a given centrality. Future $dE_T/d\eta$ dependence of R_{cp} will be important to reveal hidden differences in the J/ψ suppression in different energy collisions.

Bottomonium has been detected in $p+p$, $d+Au$ and Au+Au collisions in the central and forward rapidities. PHENIX measures the dilepton mass peak containing $\Upsilon(1S+2S+3S)$. The data collected in $p+p$ collisions provided the measurement of Υ family cross section in three rapidity bins (Figure 5-left). The nuclear modification factor was measured in the forward and backward rapidities in $d+Au$ collisions (Figure 5-right). Preliminary result at mid-rapidity from STAR completes the figure. The suppression of the Υ family obtained in $d+Au$ collisions shows a similar trend of stronger suppression at forward rapidity as observed for the J/ψ yield, however, the uncertainties are still too large for a definitive conclusion. Nuclear modification factors from Au+Au collisions at mid and forward rapidities are expected to be released by PHENIX soon.

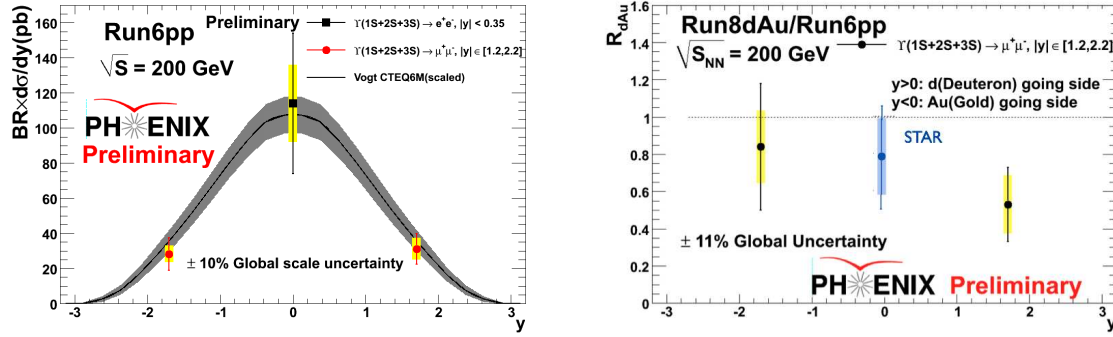


Figure 5. (Color online) Rapidity dependence of the $\Upsilon(1S+2S+3S)$ cross section in $p+p$ collisions (left) and nuclear modification factor in $d+Au$ collisions (right).

4. Conclusions

The heavy flavor program at PHENIX is tracking the source of the unexpected large suppression of open heavy flavor observed at high p_T at RHIC. Preliminary measurements using $d+Au$ and $Cu+Cu$ collisions suggest initial state effects are small at mid-rapidity, where the suppression was observed. The next phase of the program is the disentangling of the final state energy loss mechanism behind the heavy flavor suppression. The new era of silicon vertex detectors covering central and forward rapidities will allow the identification of charm and bottom decays and study their coupling to the medium.

Quarkonia have been systematically studied in several collision systems at different energies. The first measurement of charmonium excited states at RHIC imply that $42 \pm 9\%$ of the J/ψ yield comes from ψ' and χ_c decays at mid-rapidity in $p+p$ collisions. The hypothetical total dissociation of these states still cannot explain the J/ψ suppression observed in $Au+Au$ collisions. The J/ψ yield is suppressed in $d+Au$ collisions over the entire rapidity coverage with a stronger suppression at forward rapidity. The same behavior is also observed for the $\Upsilon(1S+2S+3S)$ yield, though with large uncertainties. The nuclear modification of the J/ψ yield in $d+Au$ collisions is not a linear function of the density weighted nuclear thickness as originally assumed. This discovery can perhaps reconcile the cold nuclear matter estimations with the observation of stronger J/ψ suppression at forward rapidities in $Au+Au$ collisions. The centrality dependence of the nuclear modification factor of the J/ψ yield revealed to be the same at forward rapidity in $Au+Au$ collisions at $\sqrt{s_{NN}} = 62$ GeV and $\sqrt{s_{NN}} = 200$ GeV, hence supporting previous comparisons between RHIC and CERN-SPS results. However, for a given number of participants, the energy density of the system should be different. A future R_{cp} vs. $dE_T/d\eta$ plot from different energy collision samples will be important to understand how J/ψ is suppressed in $Au+Au$ collisions.

References

- [1] A. Adare et al. *Phys. Rev. Lett.*, 98:172301, 2007.
- [2] Y.L. Dokshitzer and D.E. Kharzeev. *Phys.Lett.*, B519:199–206, 2001.
- [3] S. Wicks, W. Horowitz, M. Djordjevic, and M. Gyulassy. *Nucl.Phys.*, A784:426–442, 2007.
- [4] N. Armesto, M. Cacciari, A. Dainese, C.A. Salgado, and U.A. Wiedemann. *Phys.Lett.*, B637:362–366, 2006.
- [5] A. Adare et al. *Phys. Rev. Lett.*, 98:232002, 2007.
- [6] E. Scomparin. *J. Phys.*, G34:S463–470, 2007.
- [7] S.S. Adler et al. *Phys. Rev.*, C71:034908, 2005.
- [8] T. Matsui and H. Satz. *Phys. Lett.*, B178:416, 1986.
- [9] A. Adare et al. Heavy Quark Production in p+p and Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at $\sqrt{s_{NN}}=200$ GeV. *nucl-ex/1005.1627*, 2010.
- [10] B.I. Abelev et al. *Phys.Rev.Lett.*, 98:192301, 2007.
- [11] M. Cacciari, P. Nason, and R. Vogt. *Phys. Rev. Lett.*, 95(12):122001, 2005.
- [12] W.M. Alberico, A. Beraudo, A. De Pace, A. Molinari, M. Monteno, et al. Heavy-flavour spectra in high energy nucleus-nucleus collisions. *hep-ph/1101.6008*, 2011.
- [13] S.S. Adler et al. *Phys.Rev.*, D74:072002, 2006.
- [14] M. Durham. Recent phenix results on open heavy flavor. *This proceedings*, 2011.
- [15] S.S. Adler et al. *Phys. Rev.*, D76:092002, 2007.
- [16] R. Nouicer. *Nuclear Instruments and Methods in Physics Research Section B*, 261(1):1067, 2007.
- [17] J.S. Kapustinsky. *Nuclear Instruments and Methods in Physics Research Section A*, 617(1):546, 2010.
- [18] A. Adare et al. J/ ψ suppression at forward rapidity in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. *nucl-ex/1103.6269*, 2011.
- [19] K.J. Eskola, H. Paukkunen, and C.A. Salgado. *JHEP*, 0904:065, 2009.
- [20] A. Adare et al. Cold Nuclear Matter Effects on J/ ψ Yields as a Function of Rapidity and Nuclear Geometry in Deuteron-Gold Collisions at $\sqrt{s_{NN}} = 200$ GeV. *arXiv:1010.1246*, 2010.
- [21] A. Adare et al. Ground and excited charmonium state production in p+p collisions at $\sqrt{s}=200$ GeV. *hep-ex/1105.1966*, 2011.
- [22] A. Adare et al. *Phys. Rev.*, D82:012001, 2010.
- [23] J. P. Lansberg. *Phys. Lett.*, B695:149–156, 2011.
- [24] M. Butenschön and B.A. Kniehl. *Phys. Rev. Lett.*, 106(2):022003, Jan 2011.
- [25] N. Brambilla, S. Eidelman, B.K. Heltsley, R. Vogt, G.T. Bodwin, et al. *Eur.Phys.J.*, C71:1534, 2011.
- [26] A. Adare et al. *Phys. Rev. Lett.*, 104:132301, 2010.